Compression of the dc drain current by electron trapping in AlGaN/GaN modulation doped field-effect transistors

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(Received 15 November 2000; accepted for publication 23 February 2001)

The frequently observed dc drain current compression of AlGaN/GaN modulation doped field-effect transistors is associated with partial loss of the two-dimensional electron gas caused by electron trapping. The behavior of the temperature-dependent electron concentration and persistent photoconductivity at low temperature in the AlGaN/GaN modulation doped heterostructure are indicative of the presence of DX centers in the AlGaN layer. Deep-level transient spectroscopy of the drain current reveals carrier trapping with activation energy of 0.28 eV. However, this value appears to be too small to explain the compression of the dc drain current or to attribute these traps to DX centers in AlGaN. [DOI: 10.1063/1.1367274]

In recent years, AlGaN/GaN modulation doped field-effect transistors (MODFETs) with high-power and high-frequency characteristics were successfully fabricated and demonstrated superb microwave power performance.[1–3] However, Nguyen, Nguyen, and Grider reported compression of the drain current at microwave frequencies and attributed it to the loss in carriers caused by the trapping of electrons in the AlGaN layer or at the surface of the device.[4] The collapse of the drain $I-V$ characteristics was also observed at low temperature in AlGaAs/GaAs MODFETs[5] and was explained by electron trapping by DX centers in the Si-doped AlGaAs layer.[6] The DX centers in Si-doped AlGaAs have been intensively studied in the 1980s.[7] They typically reveal a capture barrier, caused by large lattice relaxation, that gives rise to persistent photoconductivity (PPC) at low temperatures. Recent theoretical calculations[8,9] predicted oxygen forms DX-type centers in wurtzite AlN with the oxygen atom relaxed along the [0001] direction. McCluskey *et al.* presented experimental evidence that oxygen is indeed a DX center in $Al_xGa_{1-x}N$ for $x>0.27$, based on the Hall effect, PPC, and optical threshold measurements.[10]

In this letter, we discuss the effects of electron trapping on the electron concentration and mobility of AlGaN/GaN modulation-doped heterostructures and on the compression of the dc drain current observed at room temperature in the AlGaN/GaN MODFETs. To elucidate clearly the effects of traps, only devices with pronounced current compression were selected for this study. Drain-current deep-level transient spectroscopy (DLTS) was performed in order to further characterize the carrier traps.

The AlGaN/GaN MODFETs used in this study were grown by rf-assisted molecular beam epitaxy (MBE) on a sapphire substrate. The device fabrication was carried out using HRL's baseline process for a 0.25 μm gate length. The detailed structure and fabrication processes of the MODFETs are described elsewhere.[2] The AlGaN layer on the undoped AlGaN spacer in the MODFETs was doped with 2×10^{19} Si/cm^3, and the Al mole fraction was kept constant at 0.3 for all the AlGaN layers. Hall samples were made by forming four ohmic contacts to the two-dimensional electron gas (2DEG) in a cloverleaf pattern.

During the variable temperature Hall measurements, the electron concentration and mobility of the AlGaN/GaN modulation doped heterostructures were measured from room temperature to 70 K and then back to room temperature in the first measurement. The experiment was repeated one month later. In the second experiment, the temperature was decreased from room temperature to 80 K, and then the sample was exposed to white light from a light emitting diode (LED) for 5 min. After the light was turned off, the temperature was again increased to room temperature.

The drain current–voltage characteristics of several MODFETs were measured at room temperature with a HP4140B pA meter for the slower measurements and a HP4145B semiconductor parameter analyzer for the faster measurements. The gate and drain voltages were varied from -3.5 to -2.5 V and from 0 to 5 V, respectively, both in steps of 0.1 V. The measurement times of one device by the HP4140B and HP4145B are in the order of several minutes and seconds, respectively. In the slower measurements, the drain current–voltage characteristics were also measured under illumination with a white LED from the back of the wafer.

The drain-current DLTS, similar to the one described by Valois and Robinson,[6] was carried out by applying a pulse bias to the gate with a fixed drain voltage of 5 V. The drain-current (I_D) transients were recorded from 80 to 300 K in increments of 1 K with a digital data acquisition system. A

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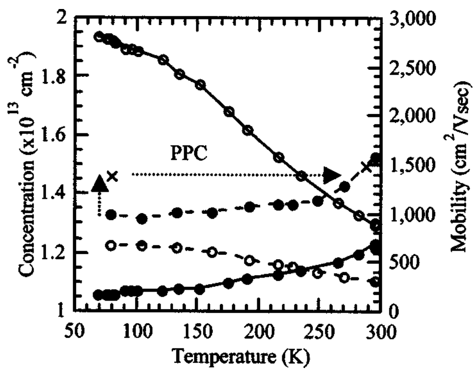

FIG. 1. Temperature-dependent electron concentration (filled circle) and mobility (open circle) in the AlGaN/GaN modulation doped heterostructure. The variable-temperature Hall measurement was carried out twice with a one-month storage in air between the measurements; the data for the first and the second measurements are shown by solid and dashed lines, respectively. The electron concentration obtained in the second measurement after turning on a white LED is shown by X.

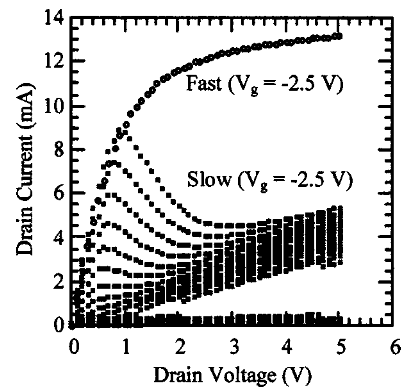

FIG. 2. The drain current–voltage characteristic of the AlGaN/GaN MODFET for slow measurements. The current–voltage characteristic for a fast measurement at the gate voltage of -2.5 V is also shown for comparison.

DLTS spectrum was obtained by plotting $\Delta I_D^{1/2}$ versus temperature, where $\Delta I_D^{1/2}=I_D^{1/2}(t_1)-I_D^{1/2}(t_2)$ for times t_1 and t_2.

Figure 1 shows the electron concentration and mobility of the AlGaN/GaN modulation-doped heterostructure at various temperatures. The solid and dashed curves are for the first and second experiment, respectively. The electron concentration (filled circles) and mobility (open circles) are significantly higher and lower, respectively, at all temperatures in the second measurement. The decreasing rate of the electron concentration becomes smaller with decreasing temperature, and at temperatures lower than 100 K, the electron concentration becomes nearly independent of temperature. A significant increase in the electron mobility is seen at low temperature in the first measurement, as expected from suppression of the scattering by ionized impurities, but not in the second measurement.

Drummond *et al.* also showed a much smaller activation energy in the AlGaAs/GaAs modulation doped heterostructure than that observed in bulk *n*-AlGaAs with the DX centers.[11] In a similar manner, the electron trapping in the AlGaN layer reduces the band bending of GaN and then the electron concentration in the 2DEG channel. The activation energy calculated from the Arrhenius plot of the electron concentration is several meV. This does not seem to indicate the thermal energy of the trap level, probably due to temperature-dependent parallel conduction via the AlGaN layer resulting from electron trapping.

The decrease in the carrier mobility, at low temperatures, by as much as a factor of 5, was accompanied by an increase of the carrier concentration during room temperature storage; this points to a loss in 2D conduction at the AlGaN/GaN interface. We suggest that this might be due to moisture absorption of the undoped AlGaN layer caused by the air exposure after the first measurement. It is not clear, whether the enhanced parallel conduction through the AlGaN layer is directly related to the formation of DX-like deep donors in AlGaN,[12] or due to another type of interface degradation during the storage. Better surface passivation in later devices seems to have eliminated this problem.

The electron concentration increased from 1.35×10^{13} to $1.48\times10^{13}\,\mathrm{cm}^{-2}$ by illumination in the second measurement, as shown with the symbol X and an arrow in Fig. 1. The concentration remains the same at all temperatures up to 280 K even after turning off the LED. This suggests the presence of PPC. The illumination near room temperature does not affect the concentration.

The temperature dependence of the electron concentration and PPC in the AlGaN/GaN modulation doped heterostructure is similar to the one previously observed in AlGaAs/GaAs modulation doped heterostructures and might also be attributed to DX-type centers in the AlGaN layer. However, it should be pointed out that the observation of PPC is not necessarily a manifestation of the presence of DX centers in the AlGaN layer. Hirsch *et al.* reported PPC at room temperature in unintentionally doped *n*-type GaN and attributed it to electron trapping in the GaN, which is not related to DX-type behavior.[12] Since in our case PPC is not observed at room temperature, it is unlikely that such traps in GaN are responsible for the observed PPC in the AlGaN/GaN modulation doped heterostructure.

Figure 2 compares the typical drain current–voltage characteristics for the faster and slower measurements. The faster measurement represents a normal FET characteristic, while that for the slower measurement shows significant compression of the drain current, which is attributed to a decrease in the channel conductance during the measurement. The latter characteristic is not affected by illumination. The amount of compression depends on the drain and gate bias. The drain current compression is similar to the collapse of the drain current characteristic observed at 77 K in AlGaAs/GaAs MODFETs,[5] which is associated with electron trapping by DX centers. Since the compression is observed here only in the slower measurement, the electron trapping is expected to be slow.

To confirm the electron trapping mechanism, the drain current transients were measured for various drain and gate voltages, see Fig. 3. The transient is more pronounced at a higher drain voltage. At a drain bias of 5 V, the transient behavior becomes more pronounced at more negative gate bias, and for a gate bias of -2.5 V, the drain current decreases by as much as 40% within 10 s.

For the DLTS measurements, the drain current transients were obtained by applying a gate pulse of -3 V with a pulse width and period of 100 and 500 ms, respectively, to the

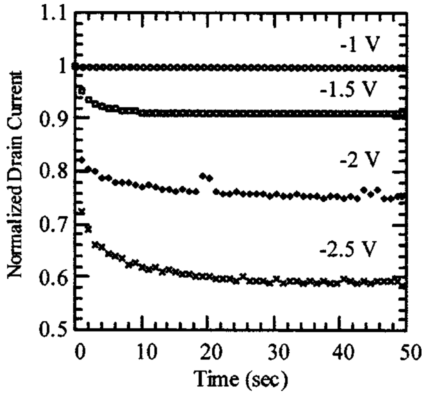

FIG. 3. Drain current transients for various gate voltages (-1, -1.5, -2, and -2.5 V). The drain voltage was set at 5 V. The drain current is normalized by dividing the drain current by the drain current at time 0 for each transient.

AlGaN/GaN MODFET biased at gate and drain voltages of -2 and 5 V, respectively. Since more electron trapping is expected at more negative gate voltages, as seen in Fig. 3, the electrons are captured during the pulse and emitted after the pulse. The DLTS spectra calculated from the transients for t_2 of 16, 28, 51, and 97 ms and the fixed t_1 of 11 ms are shown in Fig. 4. Each spectrum shows three peaks near 120 K, 160 K, and 230 K. Using an Arrhenius plot, the activation energy for the peak near 230 K was found to be 0.28 eV.

The emission time constant from this trap at 300 K is extrapolated to be 0.5 ms, while the capture time estimated from the decay of the drain current in Fig. 3 is at least 0.5 s. It should be noted that the transient consists of two exponentials with time constants of 0.5 and 15 s. Therefore, the traps with activation energy of 0.28 eV cannot be responsible for the electron trapping causing the compression of the dc drain current in the AlGaN/GaN MODFET at room temperature. Traps with considerably larger activation energy must be present in the AlGaN/GaN MODFET to explain the long current transients seen in Fig. 3. The DLTS peak for such traps may appear only at a temperature much higher than 300 K, outside the range of the present experiment.

As discussed earlier, the temperature-dependent 2DEG concentration and the PPC observed in the AlGaN/GaN heterostructure are most probably a manifestation of the presence of DX-type centers in the AlGaN layer. However, it appears to be unlikely that the traps observed here by DLTS are actually caused by the DX centers in the AlGaN layer, as 0.28 eV, the emission activation energy obtained by DLTS, is much smaller than the theoretically predicted value of 0.5 eV.[10] In our DLTS measurements, the gate bias is pulsed to a more negative voltage to fill the traps. If they are present in the AlGaN layer, the traps might stay filled with electrons when a positive or less negative bias is applied to the gate, as is in the case of the AlGaAs/GaAs MODFETs.[6,7] Therefore, the traps with an activation energy of 0.28 eV may actually not be located in the AlGaN layer. It should also be mentioned that compression of the drain current observed at microwave frequencies is more distinct at a smaller negative gate bias[4] and may not necessarily be caused by the same traps causing the dc drain current compression or those with an activation energy of 0.28 eV.

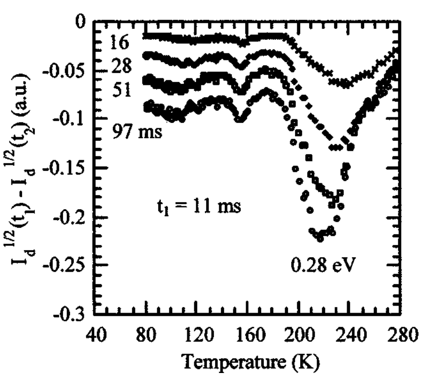

FIG. 4. Drain-current DLTS spectra with $t_1 = 11$ ms and t_2 of 16, 28, 51, and 97 ms. The emission activation energy is calculated to be 0.28 eV.

In conclusion, we have shown electron trapping in the AlGaN/GaN modulation doped heterostructure and compression of the dc drain current in AlGaN/GaN MODFET structures. The compression is observed only in slow I/V measurements; it may be easily overlooked if one performs a fast measurement of the drain current. The temperature-dependent behavior of the electron concentration and persistent photoconductivity observed at low temperature suggest that the traps responsible for electron trapping are most probably DX-type centers in the AlGaN layer. The traps with an activation energy of 0.28 eV found here by DLTS are likely to be neither responsible for compression of the dc drain current in the AlGaN/GaN MODFET nor the DX center.

For the Hall effect measurements use of facilities at Lawrence Berkeley National Laboratory's Materials Science Division are gratefully acknowledged. This work was supported by the Air Force Office of Scientific Research (AFOSR) under Contract No. F49620-98-1-0135.

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